The Golem Group

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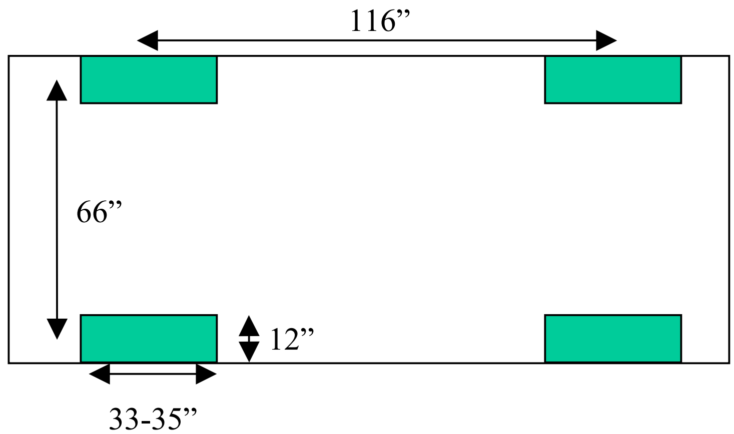
1.a.1. Describe the means of ground contact. Include a diagram showing the size and geometry of any wheels, tracks, legs, and/or other suspension components.

Our vehicle is a modified 1994 Ford F-150 4x4 pickup truck with a six-inch lift and 35x12.5 Mickey Thompson Baja Claw Radial tires. Although the tires are nominally 35 inches in diameter, by our measurement they are really about 33 inches across. (Magazine reviews of Baja Claw tires have also remarked on this "short inch" phenomenon.) The wheelbase is 116.8 inches. The front track width is approximately 67 inches and the rear track width is approximately 66 inches.



1.a.2. Describe the method of Challenge Vehicle locomotion, including steering and braking.

From a locomotion standpoint, the vehicle is a standard 4-wheel-drive off-road pickup, and the autonomous driving system will make use of the truck's normal power steering and power braking systems. The vehicle has recirculating-ball power steering, front disc brakes, rear drum brakes, and a rear anti-lock braking system.

1.a.3. Describe the means of actuation of all applicable components.

Dual Mode Steering System
A 1-kilowatt electric servomotor is connected to the steering column by a chain-and-sprocket drive. The motor has a manual clutch connected to a pushrod which is accessible to a human sitting in the driver's seat. By pulling on a knob, a human can disengage the clutch so that the steering column can be turned normally by a human driver. Our intent is for the vehicle to be manually drivable when not operating autonomously.

The servomotor is powered by a RoboteQ AX2550 DC motor driver and controlled by an IsoPod microcontroller. A potentiometer measures the absolute servomotor position.

Redundant Pneumatic Braking System
There will be two independent pneumatic braking systems. One system, intended for "normal" braking during manuevering, consists of an air cylinder delivering 200 pounds of force at 30 psi. The cylinder is alternately pressurized by one solenoid valve or depressurized by another solenoid valve, as required by a pressure sensor and computer. The force is transmitted by a steel cable to the vehicle's brake pedal lever and should be approximately equivalent to a driver applying up to 140 pounds to the brake pedal. In parallel, the second braking system is a spring-loaded air cylinder that must be kept at full pressure during vehicle motion. In the event of a

system failure or a hard emergency stop, pressure is released from the emergency system and the mechanical spring pulls the cable fully engaging the brakes.

The brake pedal can also be depressed normally by a human driver.

Speed Control
The vehicle's speed is controlled by an electric servomotor connected to the cable originally used by the vehicle's cruise control system.

At this time we don't plan to actuate the gearshift or make any changes to the truck's automatic transmission or Powertrain Control Module. For now we will suppose that the vehicle will conduct the race with the gearshift in Drive. Once we have achieved reasonable forward driving, we will consider adding a reverse driving capability and submit an addendum to this report if necessary.

1.b.1. What is the source of Challenge Vehicle power (e.g., internal combustion engine, batteries, fuel cell, etc.)?

The truck has a 5.8 liter V8 engine which provides mechanical power to the drivetrain and provides 12V electrical power to some subsystems. Additional electrical power is provided by a Honda EU3000is generator and three extra automotive batteries.

1.b.2. Approximately how much maximum peak power (expressed in Watts) does the Challenge Vehicle consume?

At maximum power the drivetrain can consume at least 164,000 Watts (220 horsepower) of mechanical energy. The electrical components should consume no more than 2000 Watts of electrical energy.

1.b.3. What type and how much fuel will be carried by the Challenge Vehicle?

The vehicle will carry 50 gallons of 87-octane gasoline.

1.c.1. What kind of computing systems (hardware) does the Challenge Vehicle employ? Describe the number, type, and primary function of each.

Two 1.5-GHz Intel processors will be used for vision processing tasks while a third is used to calculate obstacle-free trajectories, and a fourth will do state estimation based on input from the GPS, compass, and vehicle speed sensor, and send control signals to the steering, accelerator, and brake actuators to keep the vehicle on the target trajectory. One 1-GHz EPIA M-10000 VIA processor handles information from the radar.

1.c.2: Describe the methodology for the interpretation of sensor data, route planning, and vehicle control. How does the system classify objects? How are macro route planning and reactive obstacle avoidance accomplished? How are these functions translated into vehicle control?

Radar
Signal processing software provided with the Epsilon Lambda Electronics ELSC71-1A 3D radar will produce a data map of the field of view with the range, azimuth, elevation, velocity, and signal amplitude for each object detected. The azimuth is known as a function of time because the radar antenna is mechanically scanned across the field of view by a stepper motor. The range

is found from a beat signal with amplitude. The velocity is found by Doppler frequency, and the elevation angle is found by taking the phase difference between two IF channels. Range resolution is approximately 1 meter, azimuth resolution is 1.8 degrees, and elevation resolution is about 1 degree.

We will interpret abrupt changes of elevation as obstacles for the vehicle to avoid. Targets which seem to be moving relative to most of the field of view will be interpreted as moving obstacles, probably other Challenge Vehicles, and given an especially wide berth. We may be able to use the amplitude of a signal return to further classify objects (e.g., a stronger return would be expected from a metal vehicle than from a desert plant).

Vision

The vision system will consist of several video cameras, each rigidly mounted to the vehicle. We will know the rigid transformations describing the position and orientation of each camera and the radar system with respect to the vehicle coordinate system and the other cameras, at every instant of time. We also know the internal parameters of each camera, which can be obtained using standard rig calibration techniques [Bouguet].

In this case, a point in space, X, projects onto each camera. Most points will be attached to the same rigid surface, the terrain. Some will be on opposing vehicles, which can be modeled as separate rigid bodies moving in an independent manner. Still other points in space will belong to miscellaneous objects which may or may not be rigid, such as birds or clouds. For objects within the range and field of view of the radar, the vision system will know the approximate depth and velocity of locations in space. This greatly simplifies various vision tasks, since the relative change in pose between two instants of time is known. This provides a great deal of information for tasks such as feature tracking, motion estimation/segmentation, and geometric reconstruction. Objects beyond radar range will also need to be detected, tracked, and potentially identified, but since geometric information may not be easily obtained, we will use image-based techniques, such as color segmentation and 2D recognition. We will also investigate the efficacy of more advanced Level Set tracking methods [Cremers].

Detection of Other Challenge Vehicles

The initial detection of a potential vehicle will occur in both the vision and radar systems. The radar will indicate the presence of an obstructing object in its depth map, assuming the object falls within the field and depth of view. Simultaneously, the vision system will detect the presence of one or more lights of the specified alert-light color in an invariant color space (such as HSV). When this occurs, the car-detection software module will attempt to find periodic flashing, which will positively indicate the presence of an opposing vehicle. The other vehicle's position in space can be updated by tracking the image-plane coordinates of its lights and other areas-of-interest on the image of the vehicle, as well as by using radar data if any.

Detection of Miscellaneous Objects

The radar system should detect most medium and large positive obstacles in its field of view. We rely on the vision system to detect negative obstacles, positive obstacles which are significant but too small for the radar to resolve, and obstacles which are outside of the radar's field of view or which could not be seen until they were inside the radar's minimum range.

In the environment we will be traveling through, there are many regions of the image with very regular appearances. Rocky and sandy surfaces will present a difficult problem for image feature tracking due to the similarity of appearance of many nearby areas in the images. Hence, traditional structure-from-motion schemes will likely fail for the task of detecting dangerous objects. Luckily, we can exploit other information about the structure of the environment and a priori knowledge. Since the system will know the time of day, its orientation, and the lighting conditions, it can employ a shape-from-shading and shape-from-shadow system to determine the approximate position and dimensions of obstacles like large rocks or craters.

Classification of Terrain

Understanding of the type of surface on which the vehicle is traveling is essential for determining a safe speed and control technique. Paved roads or dry lakebeds will allow aggressive control at high speed, while rocky or uneven terrain must be traversed with more care. The radar system might provide some information regarding the terrain type from the amplitude of the signal return, but generally we expect better data from the vision system. Our terrain classification system will use Bayesian sensor fusion techniques, whereby the signals from the cameras and the radar are jointly interpreted to provide an estimate of the terrain type in the field of view. A statistical model will be trained using recorded data from the cameras and radar, and the parameters of the Bayesian network will be learned in a supervised manner. Other inputs to the model will be time of day and weather, both of which will influence the lighting conditions of the environment.

Determination of Local Road Geometry

While the GPS system and maps will provide medium and long-range path planning goals (waypoints), knowledge of the local upcoming road geometry can only be determined by on-board sensing. This information is crucial for short-range control and path generation. In particular, the control system will need to know the boundaries of the beaten trail, which will provide the safest route through the terrain in the absence of other obstacles. Determining these boundaries will be difficult due to the similarity of appearance of most parts of the images. From initial experiments with off-road trail video, we have determined that a distinguishable characteristic of the path is its relatively low spatial frequency. In general, a beaten path will be smoother since it will have fewer jagged rocks, little or no vegetation, and a somewhat consistent material.

Ladar

We are evaluating a ladar to be added to the vehicle. If present, this ladar will perform functions generally similar to the radar (without any monopulse elevation estimate, but with different reflectivity characteristics and a wider sweep of arc).

Route Planning

After the Route Definition Data File is provided, a nominal minimum-cost route from each waypoint to the next will be computed based on map data using a wavefront-propagation path planner. The output of this planner will be nominal desired headings and target speed as a piecewise-polynomial function of latitude and longitude across the permitted corridor between and around each waypoint pair, and this information will be stored for consideration at the appropriate point in the Route.

At all times after the vehicle passes the Departure Line, it should have an estimate of its current location and heading, and nominal desired headings and speeds for locations at its sensor horizon. Given possibly new information about obstacles in sensor range, it will use another version of the wavefront-propagation path planner to find the optimal obstacle-free trajectory that will take it to a point on the sensor horizon with as close as possible to the precomputed nominal desired heading and speed. This second algorithm will be adapted to the local planning problem in that it will more finely differentiate (x,y,theta) space and take more account of the vehicle kinematics and dynamics (e.g., steering linkage position, turning radius as a function of speed).

If there is no unobstructed path to the nominal computed route within the vehicle's field of view, the vehicle will slow down, in anticipation that the route might be blocked and it might be about to receive an E-Stop signal. If space permits, the vehicle will turn to shift its field of view and possibly find another route. If the vehicle can neither turn nor progress forward, it will come to a stop and wait for an E-Stop, or for the route to clear.

In any case, at each instant the planner should provide a desired speed and heading. PID control loops for the steering and accelerator/brake will then attempt to correct the current speed and heading. The planner is responsible for providing the PID controller with a "desired" trajectory that is within the limits of the actuators and the vehicle dynamics, e.g. the planner should not demand a turn which is unsafe at either the current or desired speeds.

1.d.1. What types of map data will be pre-stored on the vehicle for representing the terrain, the road network, and other mobility or sensing information? What is the anticipated source of this data?

Prior to the race we will create annotated maps of the Southern California/Nevada region based on our own GPS measurements and on USGS Digital Raster Graphics with 1-meter resolution, USGS Digital Elevation Models with 30-meter resolution, and US Census Bureau Tiger 2000 Transportation Layers including roads from U.S. highways to vehicular trails, for all regions for which these files are available from the California Spatial Information Library and the W.M. Keck Earth Sciences and Mining Research Information Center.

We will annotate areas and road arcs on these maps with subjectively determined cost information and store the resulting cost maps in a multiresolution data structure: something similar to the framed quadtrees of [Yahja] but tuned to the map and sensor data available (e.g., with 1-meter and 30-meter cells but without intervening levels of resolution).

1.e.1. What sensors does the challenge vehicle use for sensing the environment, including the terrain, obstacles, roads, other vehicles, etc.? For each sensor, give its type, whether it is active or passive, its sensing horizon, and its primary purpose.

One Epsilon Lambda Electronics ELSC71-1A 3D Radar. Mounted at the front of the truck, this is an active forward-pointing 76.5-GHz radar with two modes, narrow-scan and wider-scan. In wider-scan mode (which we will probably use more frequently) the radar beam is swept across a 40-degree horizontal arc and has a maximum range of 30 meters. In narrow-scan mode (which we might use at high speeds) the radar beam is swept across a 16-degree horizontal arc and has a maximum range of 40 meters. In either case, the vertical field of view is 6.4 degrees and there is a minimum range of at least 2 meters. The primary purpose of the radar is to detect significant positive obstacles and provide the vision system with depth estimates. One secondary purpose is to measure the apparent relative velocity of presumably-stationary landmarks, thus providing another measure of the vehicle's velocity in addition to the axle encoder and GPS measurement.

Two Sony DFW-VL500 Firewire Color Cameras. These passive video cameras will both point forward. One will be mounted at roof level and be level with the horizon, the other will be mounted at grille level and angled downward. The purpose of both cameras is to spot positive and negative obstacles and find a road or trail if one exists. The upper camera sees farther; the lower camera sees the near field and should be less vulnerable to sun glare. We don't plan to use these cameras as a stereo pair.

One Indigo Omega Infrared Camera. This passive long-wave infrared camera will be mounted at grille level. Its purpose is to spot thermal anomalies which could include hot vehicles and cool vegetation or water.

One Ground Whisker. This passive sensor consists of a whisker which trails (or bounces) along the ground. The resulting vibration is picked up by a microphone to evaluate ground roughness.

One SICK Laser Measurement System. We are evaluating an active SICK ladar mounted at the front of the truck. This ladar system has at least 10 meters range and 180-degree arc of sweep. It is intended to supplement the radar system in detecting positive obstacles. It is not certain yet whether this system will be available for use in the race, so in evaluating this technical paper we would like you to allow for the possibility that the ladar will not be present.

1.e.2. How are the sensors located and controlled? Include any masts, arms, or tethers that extend from the vehicle.

The radar and ladar are mounted on the front grille of the vehicle. The radar antenna is mounted on a stepper motor and sweeps back and forth in a regular pattern at 5 Hz (meaning the field of view is swept 10 times per second).

Rigidly fixed to the front of the vehicle are one Sony DFW-VL500 video camera and one Indigo Omega infrared camera.

On the roof is another forward Sony DFW-VL500, passively stabilized by a Kenyon Labs KS-8 gyrostabilizer.

A passive whisker is trailed along the ground to detect surface quality.

1.f.1. What sensors does the Challenge Vehicle use for sensing vehicle state?

Changes in the vehicle's angular orientation will be measured by a Rotomotion 6-degree-of-freedom inertial measurement unit and a Rotomotion 3-axis magnetometer. A potentiometer senses the position of the steering column. A magnetic encoder using a Hall Effect sensor measures rotation of the rear axle.

1.f.2. How does the vehicle monitor performance and use such data to inform decision making?

Velocity will be measured by the axle encoder, by the GPS receiver, and by Doppler radar measurement of landmarks thought to be stationary. If at least two of these measurements agree, and the velocity is not what is desired, then this feedback will be used to correct the cruise control/brake position.

Errors in heading will be detected by the GPS system, the IMU, and the magnetometer. If the vehicle is not moving along the desired arc, this feedback will be used to correct the steering angle.

1.g.1. How does the system determine its geolocation with respect to the Challenge Route?

A Trimble AgGPS 114 receiver mounted on the roof will provide GPS positioning with OmniSTAR subscription differential correction. A Garmin GPS V unit with Garmin GA 26C rooftop antenna and DGPS/WAAS capability is available as a backup unit. The DGPS signal will be combined with “dead reckoning” information from the inertial measurement unit and the axle encoder, and filtered by an Interacting Multiple Model estimator with two constant-velocity models with different levels of process noise.

1.g.2. If GPS is used, how does the system handle GPS outages?

In the absence of GPS, the vehicle will attempt to proceed by dead reckoning using IMU and odometry data. If the vehicle is on a known trail and following the trail is consistent with remaining on the Challenge Route, the vehicle will follow the trail and use odometry data to infer the distance traveled along it. As the uncertainty of its position grows larger, the vehicle may replan its route to avoid the Challenge Route boundaries, i.e., other things being equal it may try to remain in (what it thinks is) the center of the Challenge Route corridor, even if this is not the shortest route.

1.g.3. How does the system process and respond to Challenge Route boundaries?

Challenge Route boundaries are treated in the same way as cliffs or any other known impassable obstacle that may not be detectable by onboard sensors. They will have a soft buffer zone that may be recomputed if the uncertainty in the vehicle’s location changes significantly.

1.h.1. Will any information (or any wireless signals) be broadcast from the Challenge Vehicle? This should include information sent to any autonomous refueling/servicing equipment.

No.

1.h.2. What wireless signals will the Challenge Vehicle receive?

GPS, WAAS, and E-Stop signals.

1.i.1. Does the system refuel during the race?

No.

1.i.2. Are any additional servicing activities planned for the checkpoint?

No.

1.j. Non-autonomous control. How will the vehicle be controlled before the start of the challenge and after its completion? If it is to be remotely controlled by a human, describe how these controls will be disabled during the competition.

The truck will be drivable in normal or near-normal fashion by a human occupant using the stock steering wheel, pedals, and gearshift, when the autonomous driving system is not engaged. At this time we have no plans for remote controllability (apart from the E-Stop).

2.a. Previous Tests. What tests have already been conducted with the Challenge Vehicle or key components? What were the results?

These subsystems have been tested with positive results: steering actuation, throttle actuation, braking actuation, GPS, laser measurement system, cameras, path planner, steering encoder, axle encoder. The radar has been shown to give a minimal level of functionality but it is not clear if it will deliver the expected level of performance. So far we have done little system testing of the vehicle as an integrated whole.

2.b. Planned Tests. What tests will be conducted in the process of preparing for the Challenge?

We envision the following system tests: the vehicle autonomously steers, accelerates, and brakes in an empty environment; the vehicle autonomously drives around some trash cans in a parking lot; the vehicle autonomously follows an off-road trail. All pre-Challenge system tests will have a human in the driver's seat for oversight.

3.a. What is the top speed of the vehicle?

We plan to limit the top speed to 45 mph, because according to spec that is the maximum relative velocity at which the radar will function. If we could be sure there were no obstacles ahead, the physical top speed of the vehicle is at least 90 mph.

3.b. What is the maximum range of the vehicle?

Under favorable conditions the vehicle might get ten miles to the gallon for a maximum range of 500 miles. We are assuming mileage on the Challenge Route might be half that.

3.c. List all safety equipment on-board the Challenge Vehicle, including:

3.c.1. Fuel containment

The truck has a 45-gallon aluminum auxiliary tank mounted in the bed of the pickup truck in addition to the 18-gallon stock tank.

3.c.2. Fire suppression

The vehicle will have one 10-pound handheld A:B:C-rated fire extinguisher and one 5-pound handheld A:B:C-rated fire extinguisher.

3.c.3. Audio and visual warning devices

The vehicle will have amber flashing lamps and an audible warning device in accordance with DARPA rules.

3.d.1. How does the Challenge Vehicle execute emergency stop commands? Describe in detail the entire process from the time the on-board E-Stop receiver outputs a stop signal to the time the signal is cleared and the vehicle may proceed. Include descriptions of both the software controlled stop and the hard stop.

A soft stop signal will cause the normal braking system to fully engage and the throttle to be released. It will also alter the goal priorities of the local path planner so that the vehicle no longer places any emphasis on making progress along the Challenge Route, although it will still try to remain on the Challenge Route and avoid obstacles. While braking to a stop, the vehicle will steer so as to maximize distance from perceived obstacles and from the Challenge Route boundaries. Once the vehicle comes to a stop, the warning lights and siren will be turned off. The vehicle will remain at a stop with normal brakes engaged until the signal is cleared. At that time the lights and siren will be turned on, the local path planner will recompute a trajectory, and five seconds later the vehicle will begin movement.

The main power, the power for the emergency brake relief solenoid valve, the power for the air compressor, and the power to the throttle servo will be routed through a self-holding relay. In the event of a hard stop signal, the power to all these units will be shut off, the emergency brake will engage with maximum force and the engine will die. The only way to restart the system will be to close all emergency switches and then reset the emergency relay.

3.d.2. Describe the manual E-Stop switch(es). Provide details demonstrating that this device will prevent unexpected movement of the vehicle once engaged.

There will be six large buttons around the perimeter of the vehicle. Depressing any of these buttons will trigger a hard E-stop as described above.

3.d.3. Describe in detail the procedure for placing the vehicle in neutral. Is the vehicle towable by a conventional automobile tow truck?

The vehicle can be placed in neutral using the stock gearshift. It is towable by a conventional tow truck.

3.e.1. Itemize all devices on the Challenge Vehicle that actively radiate EM energy, and state their operating frequencies and power output. (E.g., lasers, radar apertures, etc.)

The ELSC71-1A radar radiates approximately 10 dBm of RF power at 76.5 +/- 0.2 GHz.

The LMS is a Class 1 eye-safe laser.

3.e.2. Itemize all devices on the Challenge Vehicle that may be considered a hazard to eye or ear safety, and their OSHA classification level.

There are no devices that pose a hazard to eye or ear safety, except for the audible warning device. The LMS is a Class 1 eye-safe laser.

3.e.3. Describe any safety measures and/or procedures related to all radiators.

There are no special safety procedures related to the radar or LMS.

3.f.1. Describe any Challenge Vehicle properties that may conceivably cause environmental damage, including damage to roadways and off-road surfaces.

The vehicle should have the same potential for environmental damage as a standard 4x4 pickup truck.

3.f.2. What are the maximum physical dimensions (length, width, and height) and weight of the vehicle?

The vehicle is 197 inches in length and 79 inches wide. The maximum height is 85 inches. We estimate the vehicle weight will be 5000 pounds including fuel weight.

3.f.3. What is the area of the vehicle footprint? What is the maximum ground pressure?

We estimate the vehicle footprint at 110 square inches per tire, yielding an approximate ground pressure of 11.4 psi.

References:

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[Yahja] Yahja, A., Singh, S., and Stentz, A. "An Efficient On-line Path Planner for Outdoor Mobile Robots." Robotics and Autonomous Systems. August 31, 2000. 32 (2-3): 129-143.